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THE ROLE OF SEISMIC CALIBRATION AS A CONFIDENCE-BUILDING MEASURE

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Abstract

Confidence-Building Measures (CBMs) under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) address the political goal of alleviating compliance concerns raised by chemical explosions and the technical goal of calibrating the International Monitoring System (IMS; ref. Article IV, E, and Part III of the Protocol to the treaty). The term "calibration" only appears in the treaty associated with CBMs and On-Site Inspection and has different meanings in each case. This difference can be illustrated through the use of a simple, conceptual equation:

Seismogram = source * path * instrument + noise,

where * stands for convolution (we use the seismic case, but the equation applies to the infrasound and hydroacoustic cases as well). This equation states that a seismogram at a given receiver is a function of the source, path, and instrument (with noise added). The purpose of calibration is to reduce the uncertainty of the terms on the right side of the equation so the left side can be predicted accurately. For OSI, calibration is aimed at the instrument term. Seismic calibration is aimed at the path term; i.e., once the path and instrument terms are known, the source can be accurately determined. Calibration of the path term is carried out either empirically using known sources or through earth models to estimate the path term. Known sources are called "calibration" or "reference" events and are characterized by ground truth. In practice, the precision of the ground truth varies for different types of reference events. Mining explosions or explosions carried out for the express purpose of calibration have the highest degree of accuracy since the location and origin time are known from direct observation. An example of a calibration event with less accurate ground truth would be an earthquake that occurs within a local network with large enough magnitude to be observed regionally. Such events have location accuracy typically less than 5 km. Outside of mining regions and seismically active regions, the path term will need to be estimated with earth models developed from studies such as seismic refraction experiments. These models will be the result of the integration of all available information and need to be tested—most likely with dedicated calibration experiments—over the region for which they are considered to be valid. To develop these path calibrations is clearly a large effort that requires the cooperation scientists all over

the world to strengthen the nuclear explosion monitoring capability by developing and sharing reference data sets. Guidelines for effective participation are emerging: (1) Guidelines and Reporting Formats for the Implementation of Confidence-Building Measures, CTBT/PC-9/1/Annex II/Appendix IV, pages 26 to 43, August 1999. (Available from www.ctbto.org.) (2) Knowledge Base Contributor's Guide, SAND2000-0442, Feb. 2000. (Available from www.ctbt.rnd.doe.gov.) (3) The Integration Process Design for Incorporating into the Department of Energy Knowledge Base, SAND00-0597, May 2000. (Available from www.ctbt.rnd.doe.gov.)

Key Words: calibration, confidence-building measures, mining explosions

Introduction

Nuclear explosion monitoring capability is fundamentally dependent on monitoring station installation. These stations are being installed during the preparatory phase prior to entry-into-force of the Comprehensive Nuclear-Test-Ban Treaty and they will provide essential detection capability. However, once installed, their full potential, particularly location capability, will not be realized unless calibrated. Calibration is not required by the treaty, but rather is a voluntary activity allowed under the Confidence-Building Measures part of the treaty. There are many aspects of calibration as evidenced by the several terms of the descriptive equation; furthermore the importance of calibration to each term is different for each monitoring technology and will be implemented to some degree for all technologies as part of normal installation and operations. This paper focuses on seismic calibration because of the significant role outside of operations that can be played by the global research community in conjunction with their representatives to the PrepCom. This role is larger for seismic than for other technologies primarily because of the inhomogeneity of the transmission medium of the seismic signal and can be contrasted to the considerable homogeneity of the hydroacoustic transmission medium, water. The inhomogeneity of the earth greatly complicates the path term of the equation for seismic signals. At the same time however, unlike radionuclide and infrasound technologies whose signal depends in part on ever changing atmospheric wind conditions, the seismic transmission medium is static and once characterized is essentially unchanging allowing progressive improvement and reduction of uncertainty. The fact that seismic calibration is progressive makes the long and labor intensive effort worthwhile.

Ground-Truth Data Drives the Calibration Effort

Empirical calibration is based on ground truth. Ground truth events are seismic events for which the source and location in space and time are well-known and for which the uncertainty in these parameters is well-characterized. Ground truth events include well-located earthquakes from global, regional, local and temporary networks. They also include man-made seismic sources such as mining and other industrial or military explosions, as well as dedicated calibration shots. The most basic ground truth information includes source type, and accurate location and origin time along with error estimates on these quantities. Great care must be taken to obtain accurate error estimates so that appropriate weights can be applied when combining ground truth information from many sources.

In general, ground truth accuracy trades off with coverage. For example, ground truth from global and regional catalogs provide the highest levels of coverage, but has the largest errors. The collection of the more accurate ground truth entails great expense. For a dedicated explosion, in addition to the costs of explosives and emplacement, instruments must be deployed locally to verify the accuracy of the ground truth origin time and yield by independent means. We generally sacrifice quality for better coverage and less expense, and begin empirical calibration of a given region with ground truth data from global catalogs. Higher quality ground truth information can be added to improve calibration in certain areas or to test the effectiveness of the more common, lower quality information. High quality ground truth is also critical to evaluate the regional models discussed above. To increase coverage, dedicated calibration shots can be fired near IMS stations, obtaining calibration data for all recorded paths. This is known as reciprocal or inverse calibration, and may be extremely effective for the event location problem as long as influences of near surface variations are considered.

Empirical calibrations are derived by measuring deviations (residuals) between model predictions and calibration event data. The residuals may themselves be uncertain, due to measurement errors or uncertainty in the ground truth locations, depths and origin times of the calibration events. The correction surface in some manner interpolates and averages many such data to reduce the effects of these errors. The Bayesian kriging interpolator we use applies a spatial covariance model of the residuals and allows for an explicit treatment of measurement and ground truth uncertainty (Schultz et al., 199?).

Traveltime path calibration for purposes of location requires special attention to accuracy of the ground truth information. For global catalog data, studies comparing locations to known ground truth show that an accuracy of plus or minus 15 km can be obtained by requiring a certain number of arrival-time readings and a threshold gap (Engdahl, Sweeney). This data is referred to as GT15 data, shorthand for ground truth of accuracy 15 km. The 15-km level of accuracy is significant because it is slightly less than the radius of a 1000-km^2 circle, the 1000 km^2 being the maximum area of an on-site inspection under the CTBT. The ground truth hierarchy continues with regional and local network locations, usually GT5-10 (Sandvol) and temporary, often aftershock deployments, usually GT5 (Sweeney). Additional accuracy can be obtained using locations based on surface rupture from geological or satellite observations to obtain accuracy of GT5 or less. Higher accuracy can be obtained from industrial blasts, for which accurate locations can be obtained, but often less accurate origin times (Stump, Pearson, Harris). These can be described as GT2. Finally, dedicated explosions of tens of meter and millisecond level accuracy are designated GT0 (Leith…). The Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission recommends that calibration explosions be known to within 100 m location and 0.1 s timing accuracy (PrepCom, 1999).

We must verify the correction surfaces generated by interpolating ground truth data. This is commonly done using cross-validation procedures, in which events are analyzed using calibration values generated by all other events and misfit statistics are collected as all events are examined in turn. Dramatic improvements in location quality have been shown in comparisons of locations of the Racha, Georgia aftershock sequence using a regional array, before and after calibration based on GT15 data (Figure 3, Myers and Schultz).

Models Provide the Background for Regional Propagation Correction

Accurate location estimation that includes regional data requires a travel-time model appropriate to that area. Travel-time models are usually derived from one-dimensional global-average models of P and S velocities. Because such models are global averages, they do not account for regional variations in medium velocities. Regional errors in the models translate directly into location errors.

Model-based calibration approaches develop correction surfaces by tracing rays (and integrating travel times) through a two- or three-dimensional model of P and S velocities that is more representative of the region being calibrated than a global average velocity model. A hierarchy of techniques may be used to obtain velocity models, depending on available data:

1) Refraction lines provide the most direct estimate,
2) Pn, Sn, teleseismic P and S, and surface wave tomography provide partial constraints over wide regions,
3) Receiver functions provide partial constraints at a single geographic location,
4) Analogy to geophysically similar regions provides a highly uncertain estimate, but one that can be applied in the complete absence of data.

Seismic Calibration

A seismogram is the ground-motion signal from a source propagated through the earth and corrupted by background noise when recorded by the seismometer. The waveform model used to describe the observation is a convolution of source, path, and instrument response terms superimposed on additive background noise (from both earth and instrument sources):

Seismogram = source * path * instrument + noise.

The goal of seismic calibration is to estimate the path, instrument, and noise terms so that the source term can be accurately estimated during monitoring. Procedures for suppressing background noise and minimizing the uncertainty in instrument response are well developed and relatively inexpensive to apply to established stations. Uncertainty in the path term is the principal factor currently limiting the accuracy of location estimation and is the primary focus of seismic calibration.

To be effective, regional path calibration information must be made available to online for automated and human analysis. A natural way to proceed with calibration is a station by station approach for a given source region; representing corrections to simple models of regional phase traveltimes as a series of maps or lookup tables that can be quickly accessed.

As discussed above, calibrations can be empirical or model-based, or both. Empirical calibrations are preferred because they are direct calibrations and are the most certain. Their disadvantage is that they are data-limited. Model-based calibrations are comprehensive, providing corrections across larger geographic areas and are not as limited by available data. However, they are indirect calibrations and have higher uncertainty.

It is possible to combine the accuracy and precision of empirical methods with the geographical coverage afforded by propagation models by adopting a Bayesian approach. In this approach, the unified propagation model is represented by an *a priori* base model with large uncertainty specified by a prior probability distribution, modified (updated) by empirical observations having a range of uncertainties. The lower the uncertainty of the empirical data, the more control it exerts on the unified model. The base model can be any model, and in the traveltime case, for example, may be based upon tracing rays through a best-estimate, possibly three-dimensional, velocity model (Firbas, 199?). We implement this approach using a Bayesian kriging interpolator (Schultz et al., 199?), which may be made non-stationary to reflect geographically- or range-dependent uncertainties in the prior base model.

Recommended Seismic Calibration Activities

Seismology is the primary technology for monitoring the underground environment for nuclear explosions. For seismic methods to operate at their maximum accuracy, regional path calibrations need to be applied. These calibrations can be calculated from empirical calibration event data sets or regional geophysical models. Empirical calibrations are preferred since they are direct and the most certain. We recommend the following activities to aid calibration:

1) Mining explosions. The Treaty already urges States to provide to the International Data Center: explosions of 300 tons or greater.
2) Dedicated calibration experiments will most likely need to be carried out to validate models and to fill in reference event information. Reciprocal experiments as discussed above are particularly useful for calibration.
3) Local and regional seismic data. Data from local and regional networks that can locate events with 10 km accuracy or better. Such data could be made widely available through web sites (see for example <<the USGS mine explosions web page, the MedNet web page>>).
4) Integration of geophysical models. Much work has been done to create regional geophysical models. These models need to be integrated to resolve differences

parrticularly at boundaries. Such integrated models could also be maintained and updated via websites.

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